Evaluating Prognostic Parameterizations Using ARM Data at the Three Major ARM Sites

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Introduction

A single-column model (SCM) and the National Center for Atmospheric Research (NCAR) Community Atmospheric Model v2.0 (CAM2) are used to examine the sensitivity of radiative fluxes to the parameterization of cloud microphysics at the Atmospheric Radiation Measurement (ARM) Program sites. Our results generally demonstrate the superiority of parameterizations based on comprehensive treatments of cloud microphysics and cloud-radiative interactions. At the Southern Great Plains (SGP) and North Slope of Alaska (NSA) sites, and to a lesser extent at the Tropical Western Pacific (TWP) site, the SCM results simulate the ARM measurements well and are often more realistic than parameterizations found in conventional operational forecasting models.

Results from the SCM experiments indicate that atmospheric radiative fluxes are sensitive to parameterization of ice particle effective radius (R_{eff}) by up to 30 W m^{-2} on a daily time scale. The SCM results also show that the variance of modeled R_{eff} is considerably smaller than observed and can alter modeled radiative fluxes by up to 25 W m^{-2} on the daily time scale and 5 W m^{-2} on the seasonal time scale.

Results from a series of one-year runs of CAM2 confirm the sensitivity of modeled radiative fluxes to the underestimation of the R_{eff} variance found by the SCM. An experimental run of CAM2 that employed a more realistic variance of R_{eff} produced changes in the zonal mean longwave cloud forcing of up to 8 W m^{-2} in the Intertropical Convergence Zone (ITCZ) region and 5 W m^{-2} in the Northern Hemispheric mid-latitudes during a 3-month period (JJA). In a 20°x30° region including the SGP site, the increased variability of R_{eff} results in changes in the longwave cooling rate of up to 0.1°K day^{-1} that agrees well with results from the SCM.

Single Column Model (SCM)

Forcing data for the SCM consists of horizontal advective fluxes of heat, moisture and momentum, surface temperature and surface heat fluxes. In this study, forcing data at each ARM site was produced from the 0-24 hour fields from each daily forecast made by the National Centers for Environmental Prediction (NCEP) Global Spectral Model (GSM) (Scripps version). This forcing data set currently extends back to May, 2000.

The SCM is configured with a vertical resolution of approximately 25 mb (53 vertical layers) and a time step of 7.5 minutes. The SCM employs a prognostic cloud parameterization (Tiedtke 1993) and interactive cloud optical properties (liquid water clouds: Slingo 1989; ice clouds: McFarquhar 2002). Particle effective radius is parameterized using the schemes of Bower et al. (1994) for liquid droplets and either McFarquhar (2001), Wyser (1998), or Suzuki et al. (1993) for ice crystals. The McFarquhar (2001) scheme is the default (control) parameterization for the SCM. For a more detailed description of the SCM see Iacobellis and Somerville (2003).

The SCM was run from May 2000 to August 2003 using the GSM forcing data. Relaxation advection was applied (Randall and Cripe, 1999) to keep the modeled profiles of temperature and humidity close to observed values. The SCM results compare very favorably with the ARM surface observations of downwelling surface shortwave radiation (DSSR) at all three ARM sites (Figure 1). Overall, the results from the SCM using prognostic clouds compare much better with the observations than the results from the GSM which used a diagnostic cloud parameterization.

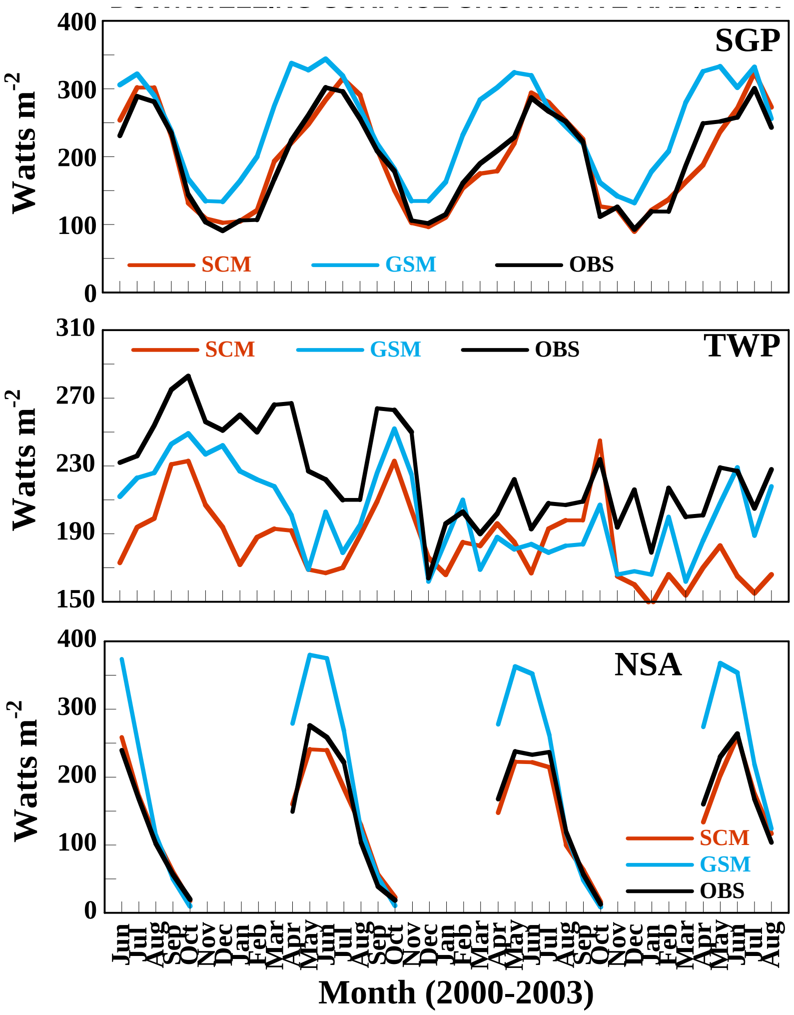


Figure 1. Monthly mean downwelling surface shortwave radiation from the SCM, GSM, and ARM observations at the Southern Great Plains (top panel). Tropical West Pacific (TWP), and North Slope of Alaska (NSA) for the period May 2000 to August 2003.

During a 3-month period at the SGP site (JJA 2000), the SCM results reproduce much of the observed temporal variability (Figure 2). This performance is typical of the entire period shown in Figure 1. The modeled 3-month mean radiative flux values from the SCM are within 10% of ARM surface and satellite observations. The probability distribution of daily mean cloud amount from SCM also compares well with GOES satellite observations (not shown). Correlation coefficients between 5-day means from the SCM and ARM observations are consistently above 0.70.

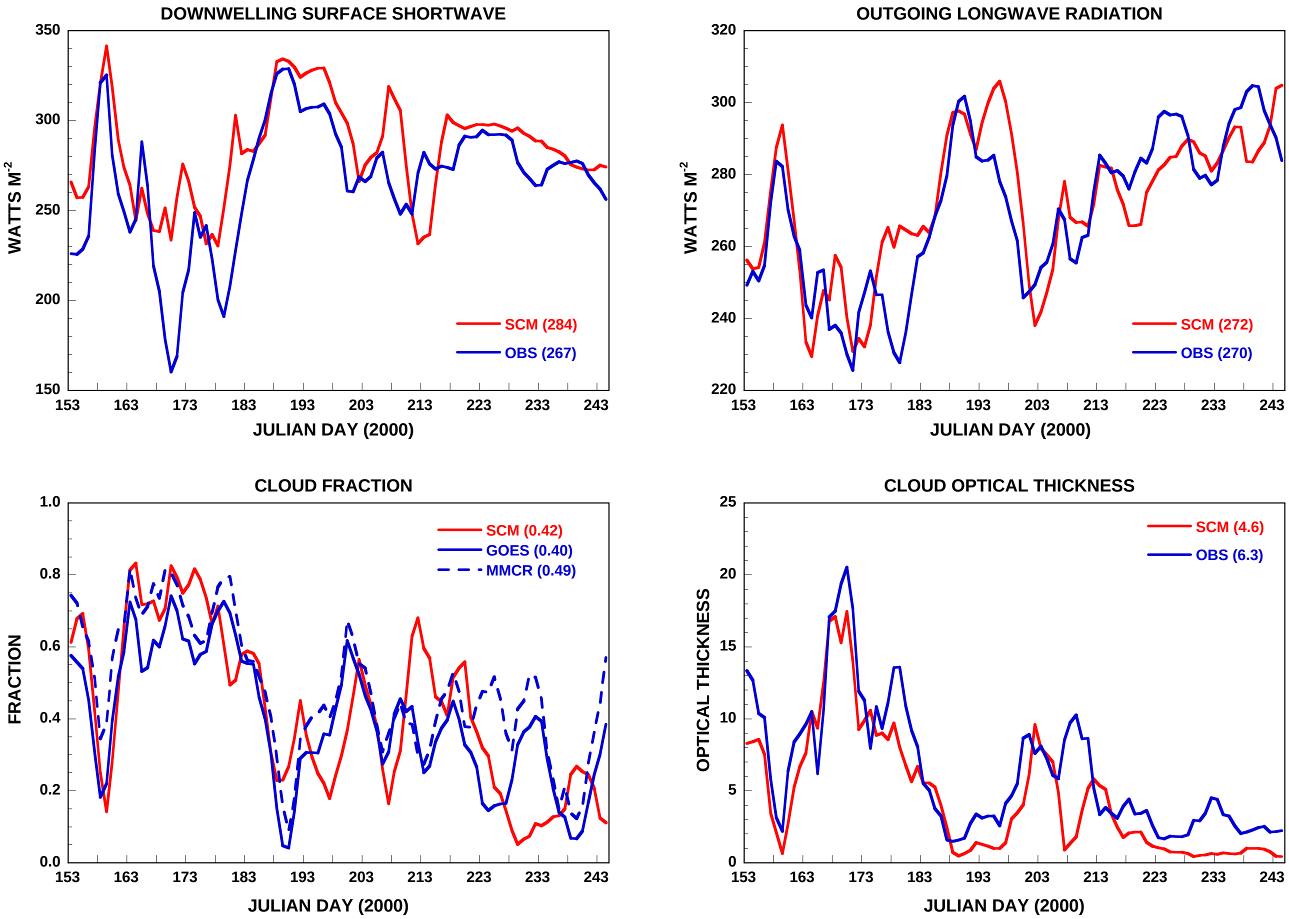


Figure 2. Results from the control version of the SCM at the SGP site for the period June-August 2000 along with ARM surface and satellite observations. The numbers in the parentheses are the 3-month mean values.

Our analysis indicates that the SCM results are sensitive to the parameterization used to calculate effective ice particle radius (Iacobellis et al. 2003). The sensitivity of surface and top of atmosphere (TOA) radiative fluxes to effective ice particle radius scheme is up to 32 W m^{-2} on daily time scales and 4 W m^{-2} on seasonal time scales.

As shown in Figures 3 and 4, the variability of R_{eff} at any given height/pressure level is underestimated by all the parameterizations examined. An additional SCM run was performed (REIWIDE) in which an artificial random ΔR_{eff} was added to the parameterized value of R_{eff} to increase the modeled variability.

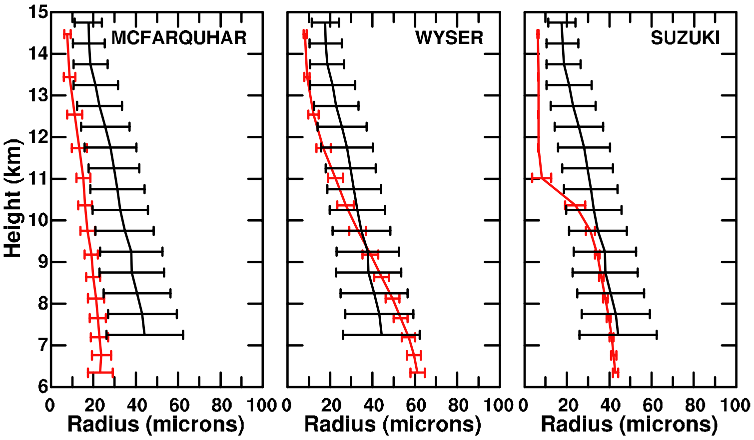


Figure 3. Vertical profile of ice particle effective radius from SCM runs (red) and MMCR measurements (black) for JJA 2000. Each SCM run used a different parameterization to calculate the effective ice particle radius. The width of the horizontal bar is 2σ. MMCR measurements obtained courtesy of Jay Mace (Mace et al. 1998).

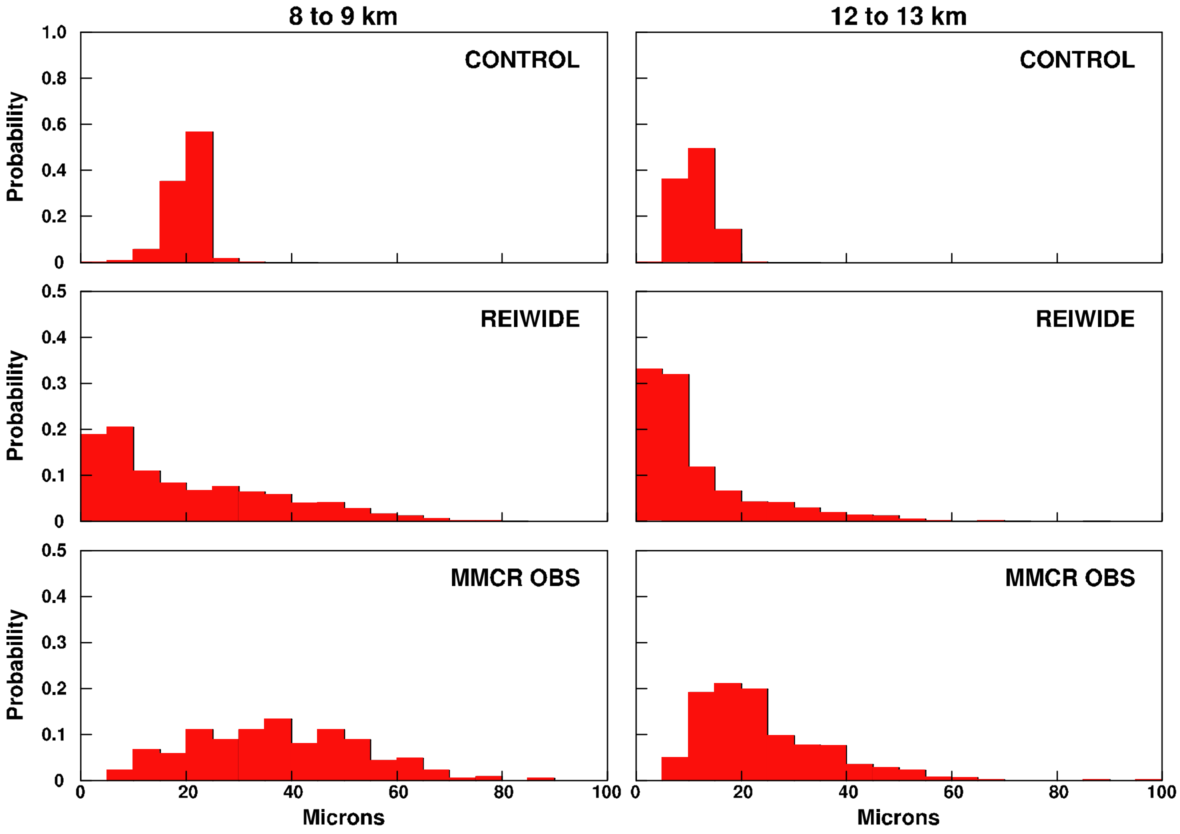


Figure 4. Probability distribution of ice particle radius for the period June-August 2000 at 8-9 km (left column) and 12-13 km (right column) from two SCM runs and from MMCR measurements at the SGP site. SCM run REIWIDE included a random ΔR_{eff} to artificially increase the R_{eff} variability.

The variability of R_{eff} from this run more closely matches that seen in the observations (Figure 4). Our analysis indicates that the sensitivity of surface and TOA radiative fluxes to this underestimation of variability is up to 26 W m^{-2} on daily time scales and 5 W m^{-2} on seasonal time scales. The vertical profile of the longwave heating rate is also sensitive to the underestimation of R_{eff} variability (Figure 5).

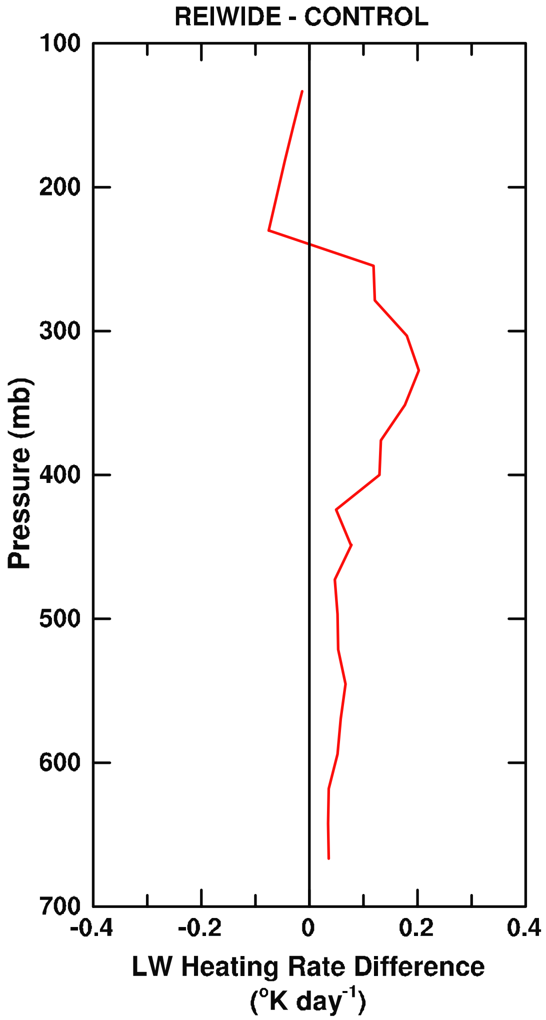


Figure 5. Vertical profile of the mean difference in longwave heating rate between SCM runs REIWIDE and CONTROL.

Community Atmosphere Model v2.0 (CAM2)

A series of three one-year runs were made with CAM2 (T21 version, 32 x 64 resolution). Each of these runs started on 01SEP00 and only the last three months (JJA) are analyzed. The first run (STANDARD) is the standard CAM2 configuration. In the second run (REIMCF) the ice particle effective radius parameterization was replaced with the McFarquhar (2001) parameterization. In the third and final run (REIMCFWIDE) an artificial random ΔR_{eff} was added to the McFarquahar (2001) scheme to simulate increased R_{eff} variability.

The vertical profiles of R_{eff} from the CAM2 run STANDARD and run REIMCF are shown in Figure 6. Note that CAM2 and the SCM use different definitions of R_{eff}. As a result, the magnitude of R_{eff} in CAM2 is approximately 1.7 times that of R_{eff} in the SCM.

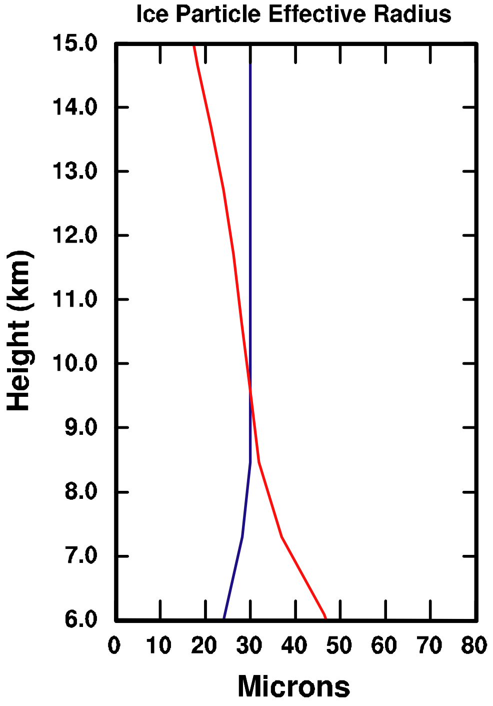


Figure 6. Vertical profile of R_{eff} from the CAM2 run STANDARD (blue) and from run REIMCF (red).

For this study the results from two regions representing the Tropical Western Pacific and the Midwestern U.S. are analyzed (Figure 7). The random ΔR_{eff} added to the modeled R_{eff} (REIMCFWIDE) results in a broader frequency distribution of R_{eff} (Figure 8) in the Midwestern U.S. region that more closely resembles the distribution measured with the MMCR (Figure 4). The broader frequency distribution in REIMCFWIDE results in significant differences in both the shortwave and longwave cloud forcing terms (Figure 9). Some of these differences are due to changes in cloud amount and/or the cloud water path, most notably in the mid-latitude storm tracks. However, in other regions such as the tropics, changes in the cloud forcing terms do not appear to be due to changes in cloud amount and/or the cloud water path. The zonal mean longwave cloud forcing (Figure 10) increases by about 8 W m^{-2} in the ITCZ region in run REIMCFWIDE as compared to run REIMCF. Differences in the shortwave cloud forcing are also noted in this region, but are somewhat smaller and of opposite sign.

Vertical profiles (Figure 11) of longwave and shortwave heating rates from a region representing the Midwestern U.S. that includes the SGP site shows differences of up to 0.10 °K day^{-1} in run REIMCFWIDE. The magnitude and shape of the longwave heating rate difference is similar to that obtained from the SCM experiments (Figure 5). The changes in the radiative heating rates result in a more stable temperature profile and reduced convective mass flux in the Midwestern U.S. region. Similar features are also evident in a region of the Tropical Western Pacific except that the changes in the convective mass flux are not as apparent.

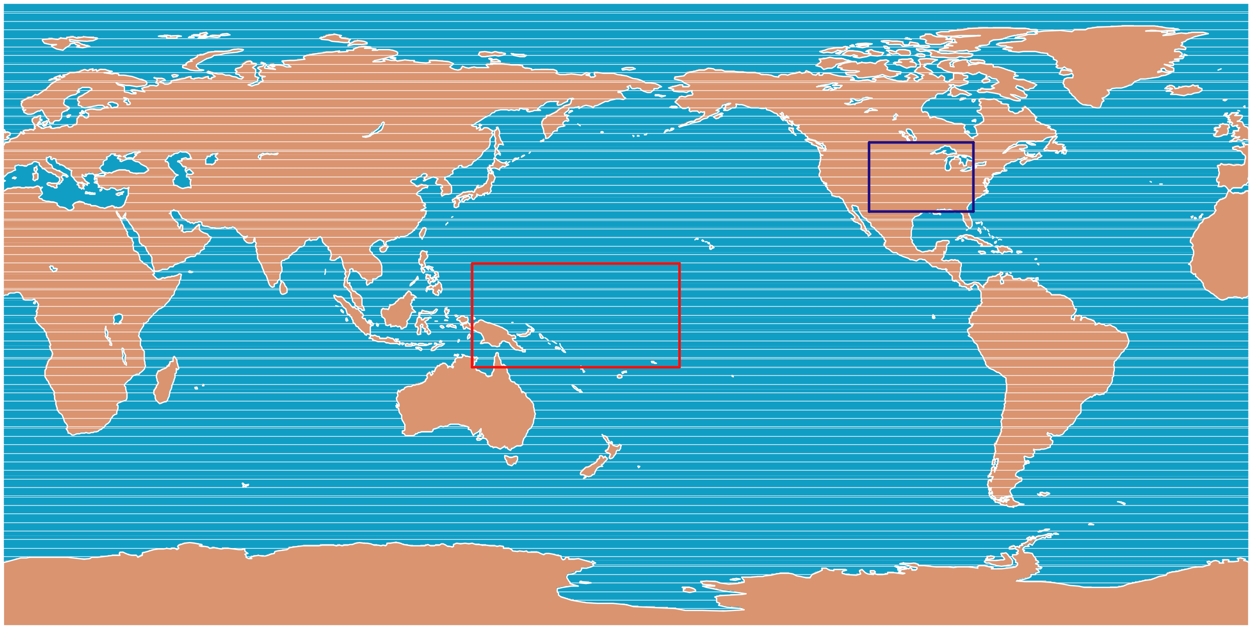


Figure 7. The regions representing the Tropical Western Pacific (red) and the Midwestern U.S. (blue).

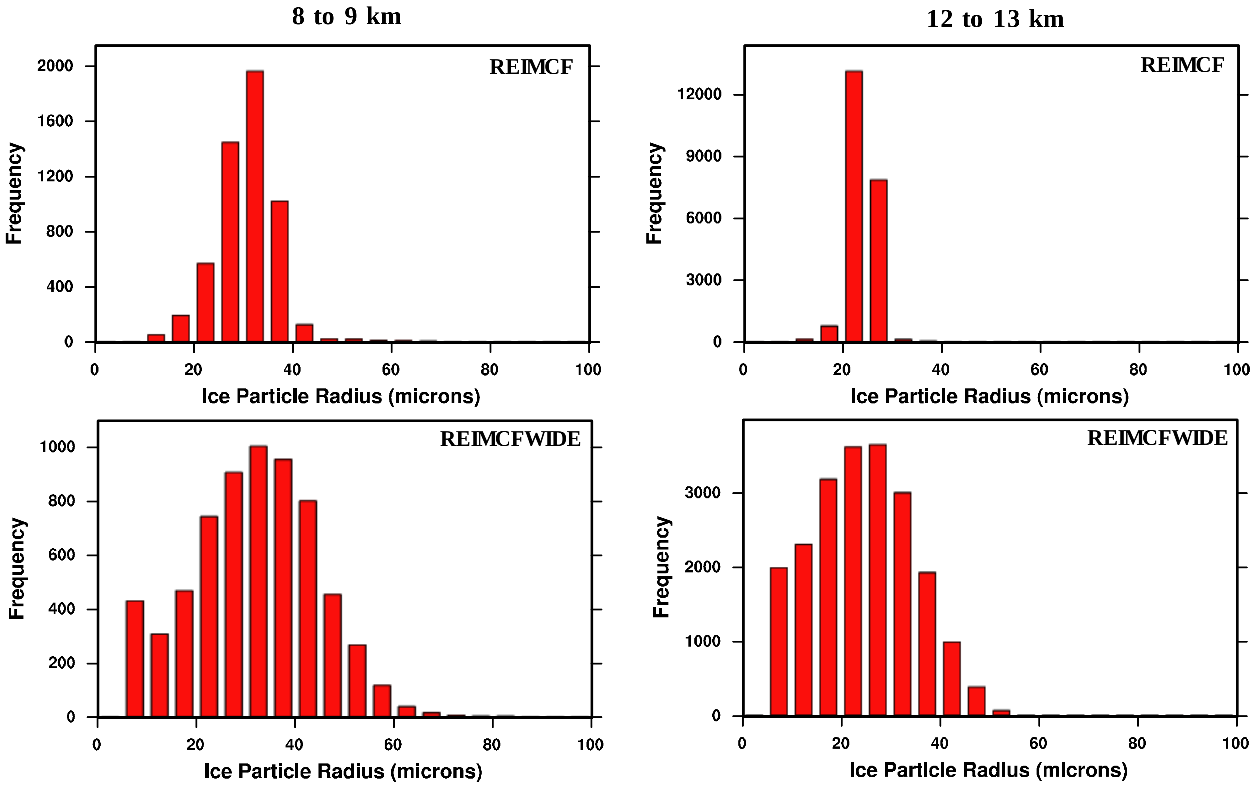
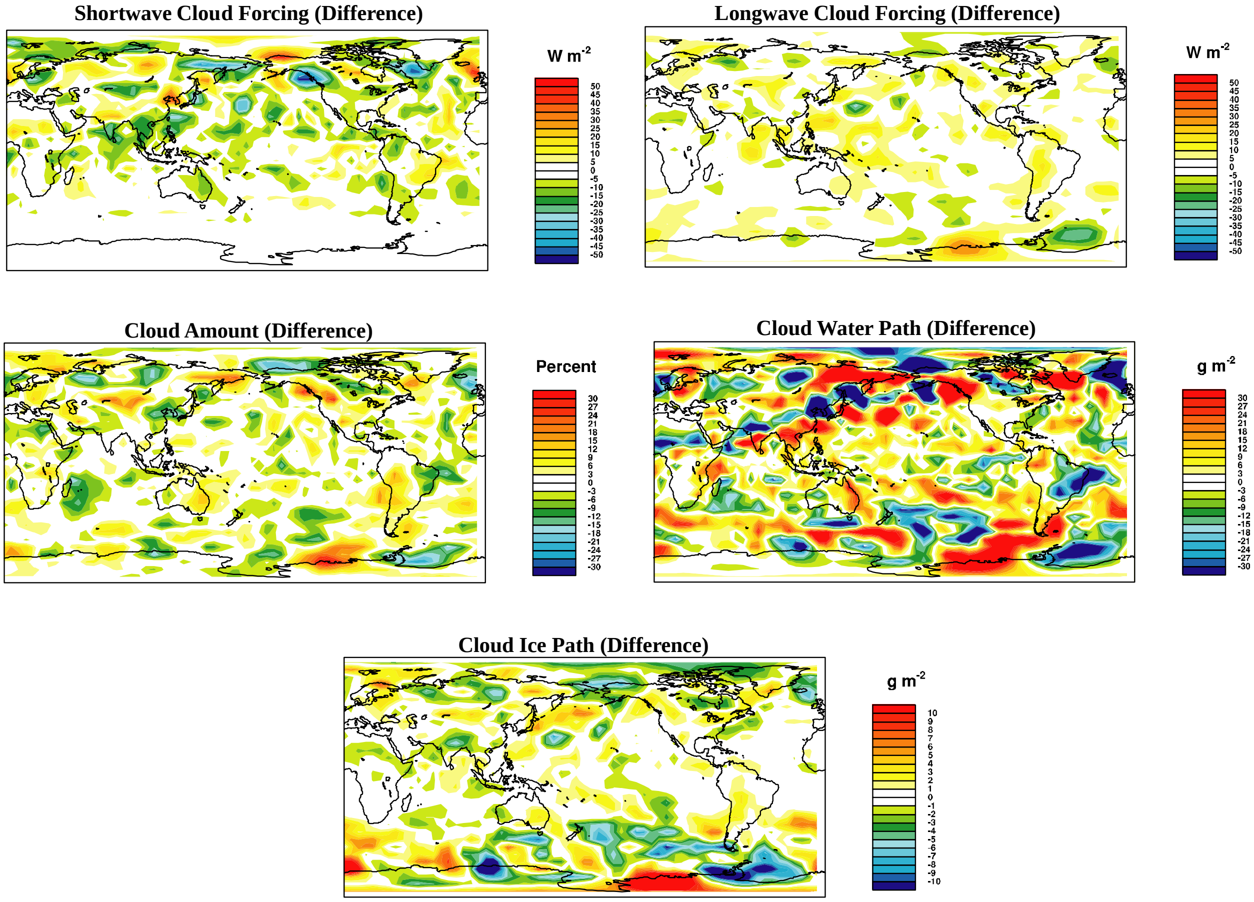


Figure 8. . Frequency distribution of R_{eff} from CAM2 runs REIMCF and REIMCFWIDE. The left-hand column are values from clouds occurring between 8 and 9 km, while the right-hand column are for clouds from 12 to 13 km.



Shortwave Cloud Forcing (Difference)

Longwave Cloud Forcing (Difference)

Cloud Amount (Difference)

Cloud Water Path (Difference)

Cloud Ice Path (Difference)

Figure 9. The difference in cloud amount, cloud water path, cloud ice path, longwave cloud forcing and shortwave cloud forcing between CAM2 runs REIMCF and REIMCFWIDE (Difference = REIMCFWIDE - REIMCF) during the period June - August.

Conclusions

- SCM results compare reasonably well with surface and satellite cloud and radiative flux observations at daily to monthly time scales.

- The various parameterizations of ice particle radius examined in the SCM produce significantly different mean profiles of R_{eff}.

- All parameterizations of R_{eff} underestimate variability compared to ARM measurements. SCM results suggest that this underestimated variability may be responsible for differences in radiative fluxes of up to 5 W m^{-2} on seasonal time scales and 25 W m^{-2} on daily time scales.

- Preliminary one-year runs with CAM2 confirm that radiative fluxes are sensitive to the variability of R_{eff}. The magnitude of the sensitivity of the radiative cloud forcing terms and the longwave heating rate are very similar to the SCM results at the SGP site.

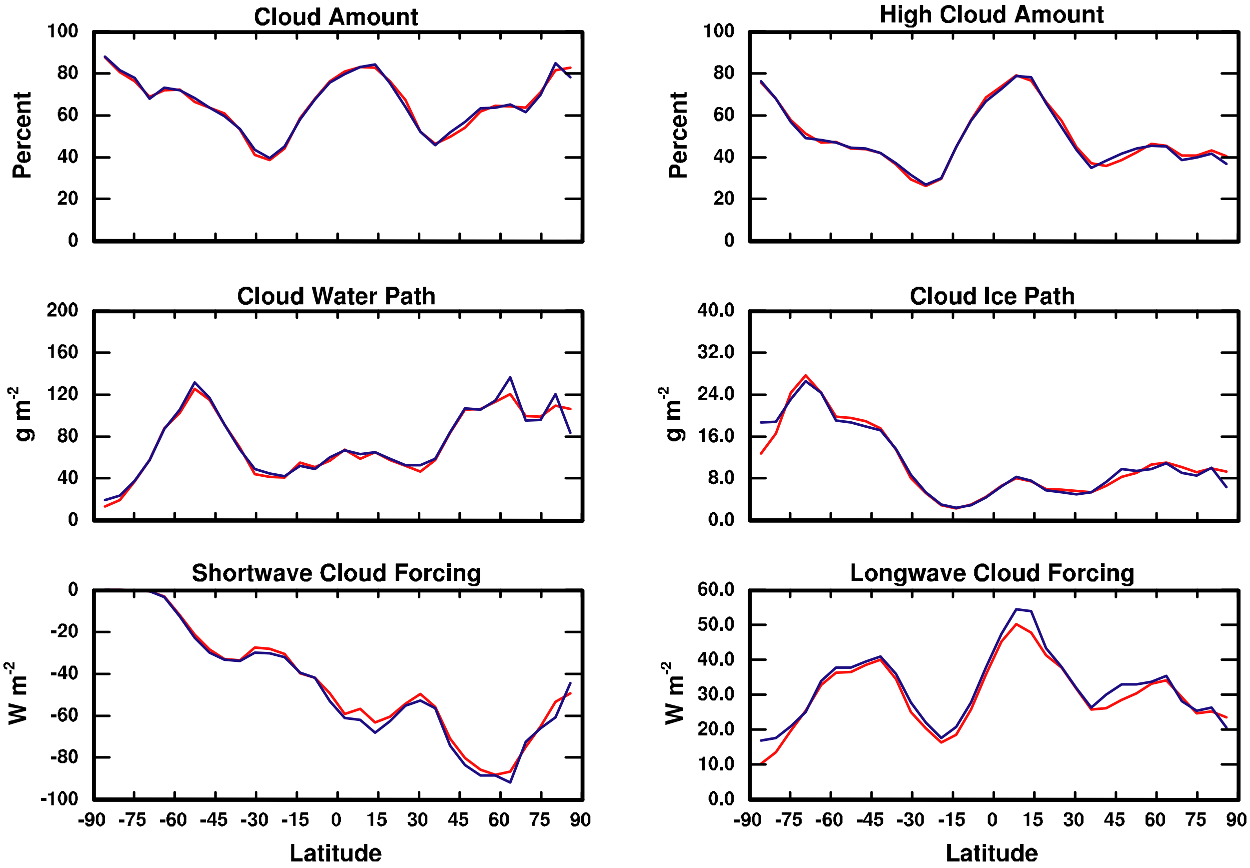


Figure 10. Zonal mean values from CAM2 runs REIMCF (red) and REIMCFWIDE (blue) for the period June - August.

Future Work

- Further examine sensitivities of ice-cloud microphysical parameterizations at SGP site.
- Expand analysis at other ARM Program sites (TWP and NSA).
- Continue to develop and test parameterizations to eliminate shortcomings found in this work.
- Continue to incorporate prognostic cloud and cloud microphysics developed in SCM into the 3-dimensional GCMs.
- Produce 10-year runs of CAM2 to validate the results found in these 1-year runs.
- Test parameterizations in short-range forecast experiments for impact on precipitation and cloudiness.

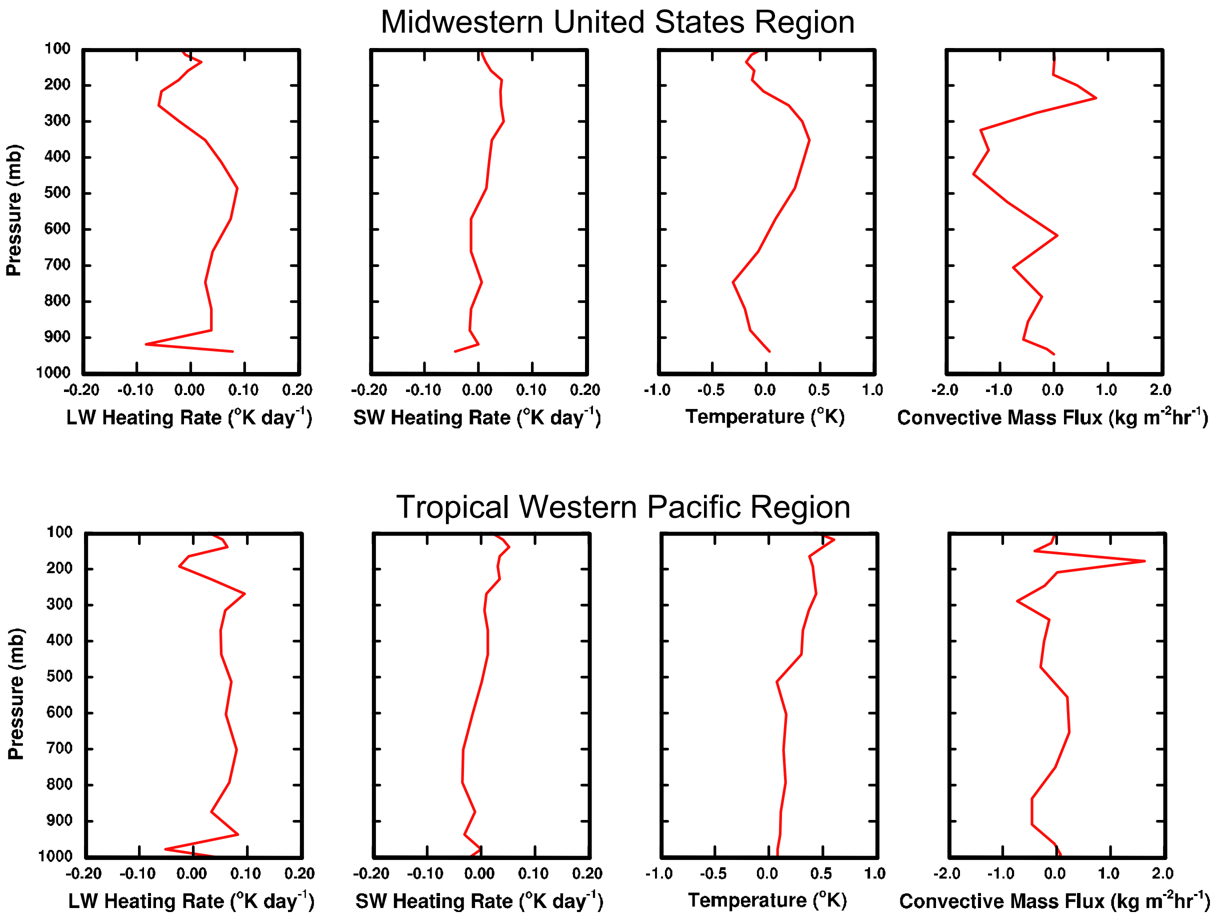


Figure 11. Differences (REIMCFWIDE - REIMCF) in the mean vertical profile of longwave heating rate, shortwave heating rate, temperature, and convective mass flux during June-August. The top row is from the region representing the Midwestern U.S. and the bottom row is from the region representing the Tropical Western Pacific (see Figure 7).

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References

Bower, K. N., T. W. Choularton, J. Latham, J. Nelson, M. B. Baker, and J. Jensen, 1994: A parameterization of warm clouds for use in atmospheric general circulation models. *J. Atmos. Sci.*, **51**, 2722-2732.

Iacobellis, S. F., G. M. McFarqular, D. L. Mitchell, and R. C. J. Somerville, 2003: On the sensitivity of radiative fluxes to parameterized cloud microphysics. *Journal of Climate*, **16,** 2979-2996.

Mace, G. G., T. P. Ackerman, P. Minnis, and D. F. Young, 1998: Cirrus layer microphysical properties derived from surface-based millimeter radar and infrared interferometer data. *J. Geophys. Res.*, **103**, 23207-23216.

McFarquhar, G. M., 2001: Comments on 'Parameterization of effective sizes of cirrus-cloud particles and its verification against observation' by Zhian Sun and Lawrie Rikus (October B, 1999, 125, 3037-3055). *Q. J. R. Meteor. Soc.*, **127**, 261-265.

McFarquhar, G. M., P. Yang, A. Macke, and A. J. Baran, 2002a: A new parameterization of single-scattering solar radiative properties for tropical ice clouds using observed ice crystal size and shape distributions. *J. Atmos. Sci,* **59,** 2458-2478.

Randall, D. A., and D. C. Cripe, 1999: Alternative methods for specification of observed forcing in single-column models and cloud system models. *J. Geophys. Res.*, **104**, 24527-24546.

Slingo, A., 1989: A GCM parameterization for the shortwave radiative properties of water clouds. *J. Atmos. Sci.*, **46**, 1419-1427.

Suzuki, T., M. Tanaka, and T. Nakajima, 1993: The microphysical feedback of cirrus cloud in climate change. *J. Meteor. Soc. Japan*, **71**, 701-713.

Tiedtke, M., 1993: Representation of clouds in large-scale models. *Mon. Wea. Rev.*, **121**, 3040-3061.
Wyser, K., 1998: The effective radius in ice clouds. *J. Climate*, **11**, 1793-1802.